Climatology of transient luminous events and lightning observed above Europe and the Mediterranean Sea

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Abstract. IIn 1999, the first sprites were observed above European thunderstorms using sensitive cameras. Since then, Eurosprite campaigns have been conducted to observe sprites and other transient luminous events (TLEs), expanding into a network covering large parts of Europe and coastal areas. In 2009 through 2013, the number of optical observations of TLEs reached a peak of 2000 per year. Because of this unprecedented number of European observations, it was possible to construct a climatology of 8319 TLEs observed above 1018 thunderstorm systems, and study for the first time their distribution and seasonal cycle above Europe and parts of the Mediterranean Sea. The number of TLEs per thunderstorm was found to follow a power law, with less than 10 TLEs for 801 thunderstorms and up to 195 TLEs above the most prolific one. The majority of TLEs were classified as sprites, 470 elves, 280 halos, 70 upward lightning, 2 blue jets and 1 gigantic jet. The climatology shows intense TLE activity during summer over continental areas, and in late autumn over coastal areas and sea. The two seasons peak respectively in August and November, separated by March and

April with almost no TLEs, and a relative minimum around September. The observed TLE activity, i.e. mostly sprites, is shown to be largely consistent with lightning activity, with a 1/1000 of observed TLE to lightning ratio in regions with most observations. The overall behavior is consistent among individual years, making the observed seasonal cycle a robust general feature of TLE activity above Europe.

1 Introduction

Three decades ago, a test low-light camera recorded a sprite (Franz et al., 1990), a spectacular discharge extending for tens of km above a thunderstorm. It was the first discovery of a whole family of upper atmosphere electrical processes, collectively known as transient luminous events (TLEs – see reviews by Rodger, 1999; Neubert, 2003; Füllekrug et al., 2006; Neubert et al., 2008; Pasko et al., 2011). TLEs occur in the upper troposphere to lower thermosphere region, between the top of thunderclouds and the lower ionosphere. They are the visible manifestation of the electrical impact of thunderstorms onto the above atmosphere. They can be made of streamers, weakly ionized plasma channels (Petrov and Petrova, 1999; Ebert et al., 2006; Luque and Ebert, 2009), roughly up to 70 km altitude; or be large diffused patches of enhanced ionization at higher altitude, where the dielectric relaxation timescale becomes comparable with that of dissociative attachment (Pasko et al., 1998). Over the years, TLEs have been distinguished in specific classes: Blue jets (Wescott et al., 1995; Boeck et al., 1995; Petrov and Petrova, 1999) are fountain-like streamers directly expanding from their leader core, and injected from the thundercloud top up to 40 km altitude towards the ionosphere (Krehbiel et al., 2008; Pasko, 2008). Sprites (Sentman and Wescott, 1993; Lyons, 1994; Sentman et al., 1995) are luminous discharges that initiate at about 70 km altitude (Stenbaek-Nielsen et al., 2010) as a consequence of the transient quasi-electrostatic field induced by large positive cloud-to-ground (+CG) lightning strokes (Pasko et al., 1997). They extend downwards to 40 km as streamers and upwards to 90 km altitude as diffuse emission, and are tens of km wide (Stenbaek-Nielsen et al., 2000). Sprite halos occur as downward moving diffuse glow at 70–80 km altitude, often accompanying sprite events but in some occasions alone (Barrington Leigh et al., 2001; Wescott et al., 2001). Elves appear as horizontally expanding diffuse emission rings of a few hundreds km diameter at about 90 km altitude, when the electromagnetic pulse of a triggering lightning stroke hits the lower ionosphere (Boeck et al., 1992; Fukunishi et al., 1996; Inan et al., 1997). Much rarer are gigantic jets (GJs), which join together apparent features of blue jets and sprites, and cause a direct connection of the thunderstorm to the lower ionosphere (Pasko et al., 2002; Su et al., 2003; Cummer et al., 2009; van der Velde et al., 2010a). Depending on the relaxation timescales at the altitude of occurrence, TLEs last from several hundreds of milliseconds (jets) down to a few milliseconds (elves). Sprites are the most commonly observed kind of TLE from ground based video observations, with global occurrence rate of about 1–3 sprite min^{-1} (Ignaccolo et al., 2008, and references therein). Satellite observations (Chen et al., 2008) confirmed a global occurrence rate of sprites of about 1 per minute, a similar rate for halos, whereas the much higher efficiency in observing elves led to an estimate of about 30 elve $\min^{-1}$ globally. A high elve/sprite ratio (6:1) was found also adopting ground based photometers, further pointing to a selection bias towards sprites in ground based video observations (Newsome and Inan, 2010).

Europe is a unique region for studies of TLEs under extremely varying conditions. The first images of European TLEs were captured by chance in 1999 over the Balkans from an aircraft based camera during the 999 Leonids-MAC airborne campaign (Gardner, L.C., and M.J. Taylor, Second Leonids-MAC workshop, Tel Aviv, 2000). The first dedicated observations were obtained in 2000 with a camera installed at the Observatoire Midi-Pyrénées, located at Pic du Midi in the French Pyrenees (Neubert et al., 2001). The authors recorded 40 sprites over the Alps and Southern France, in connection with cold fronts coming from the Atlantic. In the following years, Eurosprite campaigns were conducted during summer leading to over 700 TLE images being captured in the period from 2000 to 2008, and involving a broad range of correlative measurements including radio and infrasound (Neubert et al., 2005; Chanrion et al., 2007; Arnone et al., 2008; Neubert et al., 2008). These campaigns allowed a great number of detailed studies using specific European TLE events and thunderstorms. This includes investigations of radio signatures of TLEs and thunderstorm-induced effects onto the atmosphere (Haldoupis et al., 2004; Mika et al., 2005; Haldoupis et al., 2006; Mika et al., 2006; Farges et al., 2007; Greenberg et al., 2009; Haldoupis et al., 2010; NaitAmor et al., 2010; Füllekrug et al., 2010, 2011); investigations on infrasound signatures of sprites (Farges et al., 2005; Ignaccolo et al., 2008; Farges and Blanc, 2010); metereology of TLEs and of their producing thunderstorm (Ignaccolo et al., 2006; van der Velde et al., 2006; Ganot et al., 2007; Bór et al., 2009; Iwański et al., 2009; Savtchenko et al., 2009; Vadislavsky et al., 2009; Yair et al., 2009; Soula et al., 2010; Mäkelä et al., 2010; van der Velde et al., 2010b; Bór et al., 2018); the morphological aspects of various sprite-types (Bór, 2013). A general collection of research related to Eurosprite was included in Füllekrug et al. (2006) and presented by Neubert et al. (2008).

Eurosprite has since then expanded to become a network that joins the observational activities of tens of observers across Europe and the Mediterranean sea, exceeding 1000 observations per year. In particular, a coordination effort over 2009 through 2013 led to the production of a first database of observations with a broad coverage of regions over Europe and the Mediterranean sea. The increased number of observations was accompanied by the first detection of extremely rare phenomena such as the first GJ observed over Europe (van der Velde et al., 2010a; Kułak and Młynarczyk, 2011; Neubert et al., 2011), detailed analysis of peculiar sprite-producing thunderstorms (Soula et al., 2014, 2015, 2017), of sprite parent lightning (van der Velde et al., 2014), and elve statistics of a specific region (van der Velde and Montanyà, 2016), high speed recording of sprites (Montanyà et al., 2010), sprites signatures in radio waves (Farges and Blanc, 2011; Füllekrug et al., 2013b; Mlynarczyk et al., 2015), long-lasting TLE signatures in the ionosphere induced by rare very strong lightning (Haldoupis et al., 2012, 2013). More recent studies included also detailed impact of sprite-producing thunderstorms on the atmosphere above with consequent relativistic acceleration of electrons (Füllekrug et al., 2013a) in association with model studies (Chanrion and Neubert, 2010), impact of sprite-producing thunderstorms on the lower ionosphere (especially on the sporadic E layer) over Central European region (Barta et al., 2017) using ionosonde data, or may lead to joint studies also with detection of terrestrial gamma-ray flashes over the Mediterranean Sea (Gjesteland et al., 2015).

Such a large number of observations allows for the first time climatological studies to be performed over Europe and the Mediterranean sea: a Southern Mediterranean perspective was presented by Yair et al. (2015) and an introduction to the climatology presented here was discussed by Arnone and Dinelli (2016). Despite being inhomogeneously distributed, the number of ground-based observed sprites largely exceeds that acquired globally from satellites over equivalent periods of time (Chen et al., 2008). They give therefore an essential contribution to climatological studies, which remain fundamental for understanding the global role of TLEs in the atmosphere (see e.g., reviews by Pasko, 2010; Pasko et al., 2011): e.g. answering questions on the spatial and temporal distribution of their occurrence and of their impact; opening the way to comparison with other climatological atmospheric and climate data for which one-to-one analysis is not meaningful; allowing calibration of climatologies based on non-optical measurements, such as through Schumann resonances and detection at extremely low frequency (Füllekrug and Reising, 1998; Whitley et al., 2011).

A branch of European TLE-related activities that has developed over the past years and will greatly benefit from these large observational samples is that studying the impact of TLEs on the atmosphere. This include model and laboratory studies of the discharges themselves (e.g., Luque and Ebert, 2009; Ebert et al., 2010); modeling of their emissions and impact onto the atmosphere and its chemistry at local or global level (Enell et al., 2008; Gordillo-Vázquez, 2008; Arnone et al., 2008; Gordillo-Vázquez et al., 2011; Parra-Rojas et al., 2013; Neubert and Chanrion, 2013; Arnone et al., 2014; Winkler and Notholt, 2014, 2015; Parra-Rojas et al., 2015); observational studies linking chemistry to TLE occurrence (Arnone et al., 2008, 2009; Arnone and Hauchecorne, 2012; Arnone and Dinelli, 2016): a number of TLE parametrized distributions have been adopted by several of these modeling and observational studies based on regional to global lightning observations. Furthermore, investigations of the impact of sprites on the ionospheric potential and role in the global electric circuit were also brought forward (Rycroft et al., 2007; Rycroft and Odzimek, 2010; Rycroft and Harrison, 2011). More recently, a capability of investigating TLEs with high resolution spectroscopy was also developed (Gordillo-Vázquez et al., 2018) in association with optical observations of sprites.

The growth of this field of research in Europe has brought to the development of the Atmosphere-Space Interaction Monitor (ASIM) that was launched on the 2nd of April, 2018, and installed on an external platform of the Columbus Module of the International Space Station. The main objectives of the mission are related to thunderstorm activity by observing associated emissions in the near UV, near-infrared, X- and gamma-ray bands. The mission embarks two main instrument modules, the Modular Multi-spectral Imaging Array (MMIA) with two cameras and three photometers observing in the 180-230nm, 337 nm and 777.4 nm bands and the Modular X- and Gamma-ray Sensor (MXGS) observing photons of energy in the range 15keV to 20MeV with imaging capability (Neubert, 2009). A further European mission dedicated to the study of thunderstorms is the TARANIS satellite (Tool for the Analysis of RAdiations from lightNIngs and Sprites) which is planned to be launched in 2019-2020 carrying a set of instruments recording thunderstorm emission in the optical, X-, gamma- ray and radio bands (Blanc et al., 2007; Lefeuvre et al., 2008). Both space missions will exploit the coordinated ground-based observation systems and the knowledge on TLE distribution and variability discussed in this study.

In this paper, we present the distribution and seasonal cycle of TLE observations from the Eurosprite network and partners during 2009 through 2013, the period with the widest data coverage of European observations to date. The structure of the paper is as follows: the coordinated Eurosprite instrumentation and observations are presented in Sect. 2 and data analysis in Sect. 3. The results are presented in Sect. 4 and discussed in Sect. 5. Conclusions are given in Sect. 6.

2 Eurosprite instrumentation and observations

Several partners contribute to the so called Eurosprite network which provided the observations studied in this work. Eurosprite is an umbrella identifying a coordinated observational effort composed by several optical cameras permanently installed at strategic locations or temporary deployed during field campaigns throughout Europe and coastal areas. The main optical systems involved in the network are shown in Fig. 1 with their estimated coverage (see Sec. 2.5). A large number of further optical systems contribute with sporadic observations. As shown, most of Central and Southern Europe is well covered by observations, whereas there is as yet limited coverage of Eastern and Northern Europe. The Mediterranean sea and coastal areas are covered in the Northern parts by systems in Spain, France and Italy, and in the Southern parts by Israel. An overview of the optical systems involved in this study (i.e. active in 2009 to 2013) and their current status is given here below. An overall description of Eurosprite activities and early campaigns can be found in Neubert et al. (2008).

2.1 Southern Europe and the Mediterranean Sea

The first operating European sprite-watch system was installed in Southern France at Pic du Midi (42.94° N, 0.14° E, 2877 m) in the French Pyrenees to conduct campaign operations in 2000 and 2003 (Neubert et al., 2001; Neubert et al., 2005). It consisted of remotely controlled optical cameras sensitive to low-light conditions and photometers. This camera was associated to other similar systems for summer and fall campaigns, especially in 2005 and 2006 with a camera at Puy de Dome (45.77° N, 2.962° E,1465 m) and in 2008 on Mount Corona (42.46° N, 8.92° E, 2144 m) in Corsica, and at the Calar-Alto Observatory (37.22° N, -2.58° E) (Neubert et al., 2005; Chanrion et al., 2007;

Arnone et al., 2008; Neubert et al., 2008; Soula et al., 2017). A new low-light and high-resolution charge-coupled device (CCD) camera (Watec 902H) mounted on a pan-tilt unit remotely controlled by the Internet, was installed in 2009 at Pic du Midi and continuously operated. It is equipped with a 12 mm f/0.8 lens with a 31° field of view (FOV). The typical maximum range of such a high mountain system is 800 km, so that this system commonly observes TLEs over the southeastern France, the Alps, the western Mediterranean Sea and a large part of Spain (Soula et al., 2010, 2014, 2015, 2017; van der Velde et al., 2010a, 2014). Other similar cameras are located in southern France at lower altitude, in Lannemezan (43.13° N, 0.37° E, 592 m) since 2007, in Clermont-Ferrand (45.76° N, 3.11° E; 400 m) since 2010, in Rustrel (43.94° N, 5.48° E, 1020 m) since 2011. These four cameras can be operated along the year. In particular, during the period considered for this study, the Pic du Midi system was active in 2010 (mid-July to end of August), 2011 (mid-May to end of November) and 2013 (mid-August to end of September); the Corsica system in 2009 (August to mid-November), 2010 (mid-July to mid-October) and 2011 (second half of July); the Calar Alto system in 2009 (mid-April to mid-November) and 2011 (end of September to mid-December). In September 2018, a high speed remote camera system was mounted at the top of the Laboratoire Souterrain à Bas Bruit (LSBB) in Rustrel (43.93° N, 5.49° E) and plan to install another system at the Observatoire Midi-Pyrénées in 2019.

Observations taken from Spain were based on a remotely controlled camera installed at Sant Vicenç de Castellet (41.67° N, 1.85° E) and additional deployable cameras including a high-speed system (see blue circles in Fig. 1). The remotely controlled system has an observation range of about 150 to 450 km centered at the camera location, with minimum distance rarely below 100 km (about 35° high in the sky) and reaching a maximum a distance of about 600 km. The viewing had partial limitation towards Southern France because of hills blocking the lowest 12°. The system was moved to moved to Castellgalí (41.67 ° N, 1.83° E) in November 2013 were it continues operations. The cameras were operated continuously throughout the year, with observation taken when viewing conditions were clear and manually operated whenever there storms.

Observations from Italy and Switzerland were recorded by the Italian Meteor and TLE Network (IMTN), which groups over 30 cameras with fixed pointing and a few automated pointing cameras. IMTN fully covers central and Northern Italy, and adjacent regions, and has some limited sensitivity down to Southern Italy. Most cameras are close to sea level and close to cities, so that the observation range of each camera is limited to a few hundred km. Because of multiple cameras covering the same areas from different location, it is often possible to have triangulation. The most active stations (i.e. with more cameras and continuity of observations, resulting in more observations taken) are installed at Ferrara (44.83° N, 11.57° E), Tortoreto (42.66° N, 13.67° E) Contigliano (42.41° N, 12.76° E), Bologna/Medicina (44.50° N, 11.26° E), Lugano/Gnosca (46.12° N, 8.84° E), Cuneo (44.39° N, 7.48° E) and Scandicci (43.74° N,11.08° E), The southermost camera is placed in Casamassima (41.03° N, 16.82° E) since 2012. In 2010, a research camera with a remotely controlled automated

TLE detection system was mounted at the Italian Climate Observatory on Mount Cimone (44.19° N, 10.70° E), Modena, Italy. The system was moved to the Loiano Observatory (44.39° N, 11.19 ° E) in early 2013 and continues to be operational. The overall coverage from Italy includes adjacent seas, parts of central Europe and the Balkans (see yellow ellipse in Fig. 1). The cameras are operated throughout the year. The network of overlapping camera viewing demonstrated to be extremely efficient in capturing TLEs, leading for example to the only GJ captured to date over Europe (van der Velde et al., 2010a). Despite shortages in the viewing conditions and continuity of the operation of individual cameras, these regions can be considered to be largely continuously observed.

Covering the western Mediterranean Sea and adjacent regions were observations conducted from Israel by ILAN team. The TLE observing system is deployed on the rooftop of the Geophysics department of Tel Aviv University and is comprised of two panchromatic CCD cameras, mounted on a remotely controlled pan-and-tilt unit (Ganot et al., 2007) (see orange circle in Fig. 1). Observations are conducted during the thunderstorm active period of September-May every year, with a line of sight stretching up to Cyprus and Southern Turkey (Yair et al., 2009). For specific storm events, an alternative site at the Wise astronomical observatory (30.60° N, 34.76° E) in the Negev desert was used, extending the coverage to the Nile delta and beyond

2.2 Central Europe

Organized TLE observations in Central Europe started in 2007 with an optical detection site in Sopron, Hungary (47.69° N,16.44° E) with a remotely controlled monochrome analogue video camera. Due to the vulnerability of the applied pan-tilt unit, the camera used to be dismounted for the winter and reinstalled in the following year (see cyan circle in Fig. 1). Observations were taken in May to August, June to August, and July to October, in 2009, in 2010, and in 2011, respectively. Further details of TLE-related observations in Hungary can be found in Sátori et al. (2013).

Observations from Czech Republic started in May 2011 with a camera installed at at Nydek (49.67° N, 18.77° E) and continued thereafter all years round with only very minor breaks during the period of this study (5/7 to 21/7 in 2011, 5/11 to 26/11 in 2012 and 1/11 to 14/11 in 2013). See e.g. (Mlynarczyk et al., 2015). Observed TLEs occurred between May and November. The contribution from this region reached about 700 TLEs, covering Czech Republic, Slovakia, Germany, Austria, Poland, Hungary, Ukraine and extending to Italy, Slovenia, Croatia and the Adriatic Sea with distances from the observer ranging between 100 and 700 km.

First TLE research observations in Poland have been carried out during a two-week field campaign at Mount Sniezka (50.74° N, 15.74° E), the highest peak of the Sudetest, in July 2007 organized as part of Eurosprite (Odzimek et al., 2008; Iwański et al., 2009). Since summer 2011, research observations have also been made sporadically from Gliwice (50.28° N, 18.65° E) with azimuth 180-300 and from Swider (52.01° N, 21.39° E) with azimuth 300-50. These observations have been carried out using low-light sensitive cameras pointed manually, covering parts of Germany, Austria, Hungary, the Czech Republic and Poland (see pink circle in Fig. 1), as far as Southern Lithuania from Swider. Large parts of this area overlap with those covered by systems in Hungary and Czech therefore allowing triangulation. It has also to be noted that tens of sprites each year have been observed from Poland since 2009 by the Polish Fireball Network (PFN). PFN operates cameras at fixed direction over the territory of Poland with stations disseminated over central, North-West and South-West of Poland, and two stations in the East, with limited and variable viewing directions for all stations.

2.3 Northern Europe

Optical observations in northern Europe presents the basic problem that the sky is seldom dark during summer, when most Northern European thunderstorms occur. A station has been operated at Esrange, Kiruna to look for sprites over winter thunderstorms over the Atlantic coast of Norway. In Finland there is an extensive network of amateur astronomers and storm chasers related to the Astronomical Association Ursa running automatic detection software for observing bolides and other bright events in the twilight and night sky. In 2009, the northernmost European sprite and elve were recorded (Mäkelä et al., 2010). In 2009-2013, a total of 25 TLEs were observed (24 sprites, 1 blue jet).

2.4 Correlative non-optical measurements

Lightning detections from national networks were used both as guidance for pointing direction during the observations, and in order to geolocate the TLEs with their parent lightning in post-processing of TLE data. In particular, lightning data came from the VLF/LF lightning detection network LINET (Betz et al., 2009) network in Italy, Spain, Hungary, Poland and Germany. Meteorage/EUCLID data was adopted in France and nearby areas. Lightning data from Blitzortung was used by automated pointing cameras in Italy and Czech Republic. In Poland lightning detection was acquired also from PERUN and CELDN. In Finland, the lightning location data is from the Nordic Lightning Information Systems (NORDLIS Mäkelä et al., 2010). Additionally, satellite infrared images and local radar images are used both for pointing and data geolocation. For a more homogeneous analysis of lightning over Europe, we make use of data from the World Wide Lightning Location Network (WWLLN) in 2009 to 2013 over Europe and the Mediterranean Sea, both for comparison and aid in the interpretation of the TLE observations. The network is based on the recording of lightning emissions in the VLF range. The lightning detection is based on the consistent recording of a spheric signals from lightning by 5 stations of the network. Since 2009, WWLLN detectors covering and the Mediterranean Sea are placed in Portugal, Hungary, Israel and Northern Finland, whereas a new detector was activated in 2012 in the U.K. The switch on of the U.K. detector may lead to an increase in the detection rate since 2012. The overall detection efficiency is about 15-30%, biased towards strong lightning.

Several receivers were used for simultaneous electromagnetic measurements in the ELF-VLF radio range together with the optical campaigns. An ELF station located at the Geodetic observatory in Sopron, Hungary was accompanied by measurements at the Wise observatory in Israel, a remote site which has low man-made electromagnetic noise levels (Greenberg and Price, 2004). The VLF station located in Crete (CR), Greece (35.31° N, 25.08° E) is a Stanford University receiver which uses a 1.7×1.7 m^2 magnetic loop antenna, and it was accompanied by measurements at the Ben-Gurion University Desert Research Institute (30.86° N, 34.78° E) at Sde-Boker in Israel, where the station consists of two orthogonal triangular loop-antennas (Price et al., 2002). Infrasound detections from France have been used by several studies (see e.g. Farges and Blanc, 2010). The Swedish-Finnish Infrasound Network (SFIN) has been used to seek sprite signatures (Liszka and Hobara, 2006), and more later jointly with Eurosprite.

2.5 Observational coverage and detection efficiency

Figure 1) shows the location of the most representative optical systems that contributed with observations during 2009-2013 (white crosses) with an estimate of their viewing coverage (colored areas). A main issue with ground-based optical TLE observations is the unevenness of the distribution of the cameras, and the continuous changes of their viewing due to either atmospheric processes or experimental changes. Although the main observation hotspots are known (i.e. the area delimiting the observations taken by cameras capturing most TLEs), the detection efficiency is affected in a way that is not possible to characterize correctly for the largest part of the available data, for which detailed historical conditions (e.g. viewing conditions, pointing direction, operating period, observational choice of the observer when more thunderstorms are in view) were not recorded. In order to take into consideration these shortages and avoid introducing analysis biases between different cameras, we adopted and brought forward in parallel two approaches.

Firstly, an approximate coverage was evaluated adopting the same discretization as for the data analysis (see Sec. 3) and assigning to each geographical bin a score based on the viewing of the most representative camera systems (as introduced above). These systems were selected as main systems of each contributing research group or regional network, and on the basis of the continuity of their operations, area covered (e.g. if covering areas that no other cameras are reaching), and reported number of TLEs. Each of these cameras was characterized by a circular area of coverage around its location, with a radius of 300 (e.g., city) to 800 km (e.g., high mountain) depending on the geographical location and characterization by the observer. As a first approximation, a circular area was assumed for all cameras with no consideration of their actual viewing direction, assigning a score of 1 to each geographical bin within the circular area of a camera. The score was dropped to 0.5 in the 100 km closest to the camera (where the high zenith angle may prevent observing TLEs) and in the 100 km (200 km for high mountains) farther away (because of the expected drop in detection efficiency). A weight ranging 0 to 1 was then applied to the scores of each camera depending on the continuity of operations: fraction of the 5 years 2009–2013 and fraction of individual year (season). By this characterization, a bin within the viewing range of a camera operated throughout the year would get a score 1 if operated along the whole 5 years, 0.8 if operated along 4 years only. The weight was tuned also depending on known shortages or high efficiency of the cameras. The coverage distribution was then calculated integrating contribution from all cameras, resulting in maximum scores of 5 (i.e., 5 overlapping cameras) indicating the highest probability of detecting TLEs. The resulting distribution reported in Fig. 1) shows the large areas covered and highlights the areas with higher expected observing capability. This coverage was used to interpret the TLE climatology and to simulate the expected TLE distribution based on the lightning distribution. With this approach, the actual detection efficiency of individual cameras remain to be evaluated a posteriori (based on the results of this study and future dedicated case studies) but can be assumed to be partly compensated and similar among all cameras so that the overall geographical distribution can be correctly interpreted.

Secondly, in order to remove the bias produced by the uneven detection efficiency, we produced further climatologies normalized by their multi-year annual average and studied seasonal changes of the geographical distribution and monthly averages integrated over the whole area of observation both for TLEs and lightning.

3 Data analysis

The Eurosprite data used in this study include all available 2009–2013 optical images from the broad network of instrumentation described in the previous section. Individual TLE images were collected by the observers into data entries for the Eurosprite database: Each entry consists of a number of TLEs associated to an individual thunderstorm or closely related thunderstorm cells; the geographical area covered by those TLEs; the period of TLE activity; and the TLE type. TLEs recorded in one individual observation (e.g. several sprite elements in one video frame) were typically counted as one, unless they were clearly discernible as separate events. The geographical coverage of the TLEs was estimated by the observers on the basis of the camera field of view, its pointing direction and correlative meteorological data. The geolocation was performed either associating the TLE to its parent lightning stroke obtained through lightning detection networks, whenever possible, or to its parent thunderstorm through the overall lightning and cloud conditions in the region of interest. In the database, the TLE data coverage was reported with a $\pm 1^\circ$ latitude and longitude uncertainty for most observations, whereas the timing with a $\pm 1\,\mathrm{min}$ uncertainty. The $\pm 1^\circ$ uncertainty reflects both the actual spatial extent of the events, and the possible inaccuracy on their geolocation. Observations reported with higher accuracy were rounded to the closest 0.5 °, assuming a minimum spatial extent of 1 °. In order to avoid being affected by uncertainties on individual events, we studied the observed TLEs only in terms of climatology. Eurosprite data entries were binned over 0.5 ° latitude and longitude bins, and on 1-month or 1-season intervals, distributing their contribution among all bins affected by the data entry/thunderstorm area. This implies an oversampling was performed of data over a grid finer than the given uncertainty, in order to obtain an increased resolution allowed by higher accuracy observations and overlap of several observations. Possible observations of the same events by multiple cameras was either accounted for directly by the observers (this is the case of e.g. the several cameras of the IMTN network), or by removal of the database entry with less counts in case of entries that clearly overlap in space and time. The latter removal was applied only to cases reporting more than 20 TLEs to avoid rejecting cases where few different TLEs were captured by different cameras over the same region.

Lightning data from the WWLLN network was also analyzed in a similar fashion, producing a climatology with number of detected strokes within individual geographical bins in a certain season or year, and taking into consideration the total number of strokes or nighttime only strokes. The latter was evaluated considering the time of the local sunset and sunrise. For lightning climatologies, we adopted a discretization of 1° in latitude and longitude in order to be less affected by differences at too fine regional scale and allow an easier interpretation of the TLE distribution main features. In several occasions, we studied lightning data within the limited area of camera coverage or that delimiting the actual TLE observations (see further details below), and performed integration of the overall stroke counts over these regions to obtain monthly means. WWLLN lightning climatologies were used also to evaluate the distribution of TLE to stroke ratio (in this case accordingly increasing the size of the bins of the TLE climatology to 1°) and to simulate the expected TLE distribution based on detected strokes.

4 Results

4.1 Eurosprite observations in 2009–2013: TLE and lightning climatologies

In the years 2009 to 2013, Eurosprite and partners recorded 8139 TLEs over 1018 thunderstorms. The vast majority of observations were sprites, with 6994 classified events, followed by 470 elves and 280 halos. Also observed were 70 upward lightning processes, 2 blue jets and the first European gigantic jet (the latter recorded in December 2009, west of Corsica – see further details in van der Velde et al., 2010a). The remaining fraction of the events were reported as unclassified TLEs.

The climatology of TLEs above Europe and Southern Mediterranean Sea for 2009 to 2013 is reported in Fig. 2 as density of observed TLEs (TLEs $10^{-3}\mathrm{km}^{-2}\ \mathrm{yr}^{-1}$). In a similar way, the 2009–2013 climatologies of WWLLN lightning strokes as total daily counts and nighttime only counts is reported in Fig. 3 (strokes $\mathrm{km}^{-2}\ \mathrm{yr}^{-1}$). Since TLEs are observed only during nighttime, the latter should be preferred for comparison, although both maps show relevant information on the geographical distribution of thunderstorm activity over Europe and the Mediterranean sea. In particular, total lightning can be more correctly compared to climate parameters in terms of e.g., temperature, winds and precipitation. To ease comparison, the approximate area of observed TLEs over Europe is reported in the WWLLN map as reference (see white contours). The geographical extension of

TLE activity closely resembles the estimated observational coverage, therefore supporting the overall viewing range adopted for the cameras. Drops in recorded TLE rates can promptly be associated with decreases in observational coverage. High TLE activity is found in Southern France and around the Balearic Islands, in Italy and adjacent seas, then extending over Austria and the Czech Republic to the North, towards Hungary to the East, and with a separate set of observations around Cyprus. Despite the biases introduced by the location of the observational systems, some main features in the observed TLE climatology can be extracted with consideration of both observational coverage and lightning activity. Within the regions covered by the observations, the TLE main geographical distribution tends to mimic the distribution of thunderstorm activity. This is evident in the northern part of the TLE climatology where large areas with a weak TLE rate are consistent with a drop in lightning activity over vast areas, e.g. in France and Germany, and particularly over Spain contrasting with the adjacent high activity over the Pyrenees. Interestingly, some local drops in TLE rates are consistently seen in lightning, as e.g. over Eastern Italy, and likely Sardinia, a behavior that is related to nighttime lightning and less evidently to total lighting. Further similarities occur in the coastal areas of Northern Spain and Western France, were increased TLE rates are correlated with weakly increased nighttime lighting rates (more visible with a dedicated change of the color scale here not shown) and more evident in total lightning. High TLE rates are recorded at the German-Polish border with partial correlation to lightning activity (see spots of high lighting activity in this region more visible in total lightning), whereas the high activity over Czech Republic is not reproduce by a similar increase in strokes counts. In contrast, the fading of TLE activity in Southern Italy and towards Eastern Europe is due to poor coverage. The poor coverage causes similar low rates over Corsica, North-West Italy and Hungary, where local cameras tend to observe only thunderstorm at a certain distance from the observation spot.

4.1.1 TLE rates and TLE to lightning ratio

Peak TLE rate are close to or exceeds $10^{-3}\mathrm{km}^{-2}\ \mathrm{yr}^{-1}$ in a few hotspots in Southern France, Northern Mediterranean Sea, Italy, the Balkans and Poland, whereas it is typically around 0.2–0.3 in large adjacent regions. These rates and the main features of the climatology should be largely assigned to sprites, since the other observed TLEs represent a minor fraction of the database. Regarding other TLE types, almost all elves were observed over autumn/winter maritime thunderstorms, or close to coastal areas. This selection occurred also for the upward lightning, blue jets and gigantic jet (see also van der Velde et al., 2010a), whereas halos were often observed also over land. Comparison to lightning rate seen in the lightning climatologies of around 0.2–0.3 within the same regions, suggests a factor around 1000 in the ratio of observed TLE to detected total lightning on a yearly average (recall the factor 10^{-3} in the TLE climatologies). To further inspect this relationship, the TLE to nighttime lightning stroke ratio is shown in Fig. 4 and was evaluated adopting a lower resolution 1° climatology of TLEs. Typical values of the ratio are of the order 1 to 10 in regions well covered by observations, and exceed 10 in a few hotspots previously identified, particularly in the area around the German-Polish border where many more TLE per lightning stroke are observed. Taking into consideration the shortages in the observational coverage, we can evaluate an average ratio on a fraction of the geographical bins which have the highest values and drop those with low rates, which are presumably more affected by low observational coverage: when considering the top 50% of the bins, the mean TLE to nighttime lightning stroke ratio is 2.7/1000; when considering the top 30%, the mean ratio increases to 4.3/1000 (corresponding to a value of 1.3 when total lightning is used i place of nighttime lightning). Note that over the whole climatology, the rate of nighttime to total lightning has a mean value of 0.39 and median value of 0.37, with higher values over coastal ares and sea, and lower ones over continents (not shown).

4.1.2 Simulated TLE distribution

Based on the above results, we simulated an expected TLE distribution based on the nighttime lightning climatology (see Fig. 3, the observational coverage (see Fig. 1) and the estimated TLE to nighttime lightning ratio 4/1000. The observational coverage was normalized to a maximum value of 1. The results are shown in Fig. 4. The simulated TLE distribution now carries information on both lightning distribution and observational coverage, with maximum values scaled by the adopted TLE to lightning ratio. The main characteristics and typical values seen in the observed TLE climatology are found also in the simulated one: e.g., overall extension and shape of the area covered by the observations, main active regions and the overall values, features of the high rate areas and low rate ones. Also, some peculiarities of the observed climatologies can now be more easily interpreted on the base of a simultaneous effect of lightning activity and camera sensitivity. This is the case of Northern Spain and Western France (where the line features could be better reproduced with a change in the color scale – not shown) or the drop in central Spain, high rates in the Southern France coast and close to the Balearic Islands, and drop in the rates over Sardinia. The simulation reproduce correctly the observed drop over coastal Eastern Italy, Northern France, and Germany, and can also pick the behavior of the distribution observed over Hungary. In contrast, the simulation does not replicate the behavior of the climatology over Czech Republic, Slovakia and Poland, were a further refinement of the observational coverage (i.e., with consideration of the actual field of view of each camera) with dedicated studies may improve it. The simulation also expects higher than observed rates around Cyprus because of the local very intense lightning activity, although the overall area is reproduced suggesting lower weights should be estimated via dedicated studies.

The comparison of the observed and simulated TLE climatologies was evaluated quantitatively by inspecting the probability distribution functions and main statistics of the two datasets, considering a 1.0 ° lower resolution TLE climatology which was found not to differ in its statistics from the original 0.5 ° resolution climatology. The TLE and simulated climatologies have about 530 and 590 points with TLE rates greater than zero and lead to very similar probability distribution functions (not shown). Mean TLE rates for the observed climatology are 0.07, 0.10 and 0.21 (medians 0.03, 0.07 and 0.19) $10^{-3}\mathrm{km}^{-2}\ \mathrm{yr}^{-1}$ respectively considering only geographical bins with rates above 0, above 0.01 and above 0.1 $10^{-3}\mathrm{km}^{-2}\ \mathrm{yr}^{-1}$. In comparison, mean TLE rates for the simulated climatology are 0.11, 0.13 and 0.25 (medians 0.05, 0.07 and 0.20) $10^{-3}\mathrm{km}^{-2}\ \mathrm{yr}^{-1}$ respectively. The slightly higher mean values of the simulated climatology can be reduce if adopting a TLE to nighttime lightning rate of 3/1000 to 0.08, 0.10 and 0.21 (medians 0.04, 0.06, 0.17) $10^{-3}\mathrm{km}^{-2}\ \mathrm{yr}^{-1}$, although at the expenses of the median which is also slightly reduced, and of a poorer simulation of rate values over some areas (e.g., Spain and France). Overall, the adoption of a 3.5 or 4/1000 ratio seems to be adequate, supporting a posteriori what previously calculated based on the top 30% of the geographical bins with highest rates.

4.2 TLE seasonal cycle above Europe: changes to the mean geographical distribution

Seasonal averages of the geographical distribution of TLEs for individual years 2009 to 2013 are presented in Fig. 5. Grey shades show the overall area of observed TLEs during each year. As for the yearly average, the same seasonal averages are reported also for WWLLN nighttime lightning strokes in Fig. 6. Color grading refers to Fig. 2 and 3. In terms of seasonal change, TLE activity over Europe is concentrated over the sea in winter, then moves to the coastal areas in spring substantially fading in intensity, it increases and spreads over the continent in summer, and relocates again over the sea in autumn. This behavior is very consistent among the 5 years of the sample. The activity in the Southern Mediterranean Sea is consistent with the onset of maritime thunderstorms in autumn and winter (see Yair et al., 2015, for further details). Comparison to Fig. 6 shows a remarkable consistency. Firstly, the general seasonal oscillation of TLE detection between land and sea is consistent with thunderstorm activity. Secondly, detailed comparison of the hotspots of observed TLEs within a certain season corresponds in most cases to regions having the highest lightning rate (see e.g. the coastal and sea areas close to Southern France, Balearic Sea and Italy), or, vice-versa, lack of TLEs corresponds to very low lightning rates (e.g. France and Germany as mentioned above). There are clear deviations from this general behavior, e.g. in the case of autumn thunderstorms observed at the border of Czech Republic, Germany and Poland both in 2011 and 2012, or of the large summer activity observed in 2011 around the Balearic islands. Consistently, in both cases there are signatures of high lightning activity also in WWLLN data (Note that the maps show the yearly rate per km^2, so that rates in individual seasons can largely exceed that calculated over the whole year dataset).

Especially during its first months, 2009 shows a relatively poorer data coverage as compared to the following years. Despite this difference, the main features in the distribution of TLEs are repeated over the years, making it meaningful to average the 5 years together as performed in Fig. 2. In order to remove the bias induced by the clustering of optical observation systems over specific regions (see Fig. 1), we normalized the seasonal distributions of the observed TLE activity by the 2009-2013 yearly average (Fig. 2). Results of the normalization are reported in Fig. 7 as percent component of the yearly mean. The magnitude of the seasonal changes in the distribution of TLEs is now more clearly visible: TLEs are detected largely over the sea in winter followed by a negligible activity over land in spring. In summer, TLEs are detected largely over land and the higher alpine regions (see both activity over the Pyrenees and the Alps) abruptly shifting the activity over the coastal areas and sea in autumn. The strongest activity over the sea in most areas is seen in autumn, together with a maximum in activity throughout Italy. Particularly interesting is the highlight of the activity over the Southern Mediterranean Sea around Cyprus, shifting from the southern area in autumn to the northern area in winter.

4.3 TLE seasonal cycle above Europe: a monthly mean perspective

We further analyzed the seasonal evolution of TLEs calculating total average counts above Europe per month for TLEs, and for the corresponding lightning strokes (see Fig. 8). The calculation for TLEs was performed without the inclusion of ILAN observations of the Southern Mediterranean in order to have a more uniform area and a more consistent seasonal behavior; for consistency, we included only lightning data within the main TLE coverage (see grey shapes in Fig. 3). Monthly TLE and nighttime lightning counts (left panels in Fig. 8) both show a largely consistent seasonal cycle with the two active seasons (summer and autumn) separated by a deep minimum in late winter–spring (mainly March and April), and a relative minimum in late summer–early autumn (in September for TLEs and August for lightning). Maxima are reached in August and November for TLEs, and July and November for lightning. This behavior is fairly consistent among the 5 years, a part for a very active June in 2009 (which was largely affected by the most prolific thunderstorm in the sample, see 4.4). Both in summer and autumn, TLEs appear to peak some time later than lightning, but in both cases November is the most prolific month. The seasonal evolution of the number of nighttime hours should be taken in consideration when comparing summer and autumn counts since optical observations of TLEs are only available at night. This effect can be very pronounced at high latitude: For example in Northern Europe, most of the TLE observations are made in late summer (Aug-Oct) between 19 and 03 UTC. However, most of the lightning occur in June to August, which suggests that only a fraction of the TLEs occurring in the Northern Europe are observable with cameras because of the bright summer sky. In order to do so, we calculated an average nighttime duration (considering duration for Bari, Budapest, Warsaw and Granada – see dashed grey curve in Fig. 8) and normalized the monthly counts to a constant 12-hour night. The results are reported in Fig. 8 together with monthly mean lightning activity from the whole day (right panels). The overall TLE behavior is confirmed, with two distinct summer and autumn seasons now reaching similar total counts per month. An almost flat distribution between May to November is found for lightning, with an increase during July in some years.

An analysis of the time of occurrence of the observed TLEs is showed in Fig. 9 (top-left panel), reporting for each month both the average start and end of the observations (step lines) and the first and last observation (circles). The average start and end tends to be very close to the reference local midnight (at 11 UTC, dotted black line) in May to August, then increasing the average observation interval with increasing nighttime hours in autumn and winter, with a tendency to last longer during the second part of the night. First observations of each month generally start 1 or 2 hours after sunset (see bottom of the figure), whereas the last observations typically occur within 1 hour before sunrise, and sunrise. Note that the time information for February to April is based on a very limited number of observations. In Northern Europe, most of the TLE observations are made in late summer (Aug-Oct) between 19 and 3 UTC. However, most of the lightning occur in June to August, which suggests that only a fraction of the TLEs occurring in the Northern Europe are observable with cameras because of the bright summer sky.

Figure 9 also reports the seasonal evolution of the average latitude of the observations during the 5 years (top-right panel). The seasonal changes in the distribution discussed above are now summarized by an average latitude: It cycles between 41–42 ° latitude in autumn and winter, and 46–47 ° latitude in summer, with a fairly consistent behavior among the years, and therefore well characterizing the geographical change above Europe. Since the main seasonal change in TLE activity occur in latitude, no meaningful information can be extracted from average longitude.

4.4 TLE-producing thunderstorms

The seasonal evolution of the number of observed TLE-thunderstorms in 2009 to 2013 is reported in Fig. 9 (bottom-left panel) in a similar fashion as for the number of TLEs in Fig. 8. For consistency, data from Israel were again excluded from the analysis. Here we assume that each entry of the database (i.e. a collection of TLEs observed above the same thunderstorm or closely related thunderstorm cells) can be considered as an individual thunderstorm system, although some database entries may likely extend over several thunderstorm cells which were observed during the observing period. Care should thus be taken to correctly interpreting these results. Peaks in number of observed TLE-thunderstorms are reached in July, August and November, consistently with lightning activity, with about 150 TLE-thunderstorms accumulating over the 5 years. Comparison to TLE counts in Fig. 8 (top-left panel) shows that November is characterized by less but more prolific TLE-thunderstorms as compared to summer months. Out of 1018 observed thunderstorms, 801 (79%) were reported with less than 10 TLEs each, 921 (90%) with less than 20, 97 (10%) with 20 or more, 56 (6%) with more than 30, 34 (3%) with more than 40. Overall, the distribution in number of TLEs observed per thunderstorm is reported in 9 (bottom-right panel) in a log-log view. The occurrence is defined as the fraction of thunderstorms having a certain number of TLEs and normalized by the bin size (1 TLE); only cases occurring more than once are considered. The distribution follows a power law as shown by a best linear fit with coefficients –0.54 and –1.45 (dashed black line) and having a correlation of –0.96. The power law linear fits for individual years 2009 to 2013 are also shown, having correlation coefficients -0.79, -0.90, -0.91, -0.87 and -0.90 respectively. A part from 2009, the multiyear fit and fits for individual years are consistent, suggesting the law may be expected to apply for large sample of thunderstorms observed over Europe in future years. The 30 most prolific thunderstorms are summarized in Tab. 1. In particular, 12 of these thunderstorms were observed during the summer season (or late spring), and 18 during the autumn-winter season. Seven thunderstorms were reported with more than 100 TLEs each, the most prolific one being observed 29 October 2013 with 195 TLEs (193 sprites and 2 halos), followed by a thunderstorm on 10 June 2009 with 147 TLEs (146 sprites and 1 halo) and by a thunderstorm on 28 November 2011 with 140 TLEs (131 sprites, 8 elves and 1 halo). The 10 June 2009 thunderstorm makes up most of the anomalously high June TLE count found in 2009 as shown in Fig. 8 (top-left panel). Most of the prolific thunderstorms were reported with almost only sprites. Four thunderstorm were reported with a significant (greater than 30) number of elves and were all observed during the autumn-winter season (in November to January 2012 and 2013). The 12 December 2009 thunderstorms included observation of the gigantic jet discussed above, and of an upward lightning. For comparison, data for the 12 November 2011 thunderstorm observed from Israel were included in the table: this is the only case of very prolific thunderstorm observed to last only 30 minutes, whereas all other prolific thunderstorms observed above Europe and coastal areas lasted several hours each.

5 Discussion

The dataset and climatology presented in the previous section represent the first attempt to have such a coordinated ground-based climatology over Europe and Mediterranean sea. Similar continuous observations were performed over limited regions such as the US High Planes (Lyons, 1996) or in Japan (Adachi et al., 2005; Suzuki et al., 2011). Considering that only a negligible fraction of satellite observations of TLEs are currently taken over Europe (Chen et al., 2008), this is also the largest European TLE dataset available to date. The overall distribution and seasonal cycle of TLEs present robust features repeated in all the 5 years included in the sample, both as number of observed TLE-producing thunderstorms and as number of observed TLEs. This includes the two-peak seasonal cycle, with maxima in summer and late autumn, separated by two minima in March-April and less pronouncedly in September-October. The two active seasons are due to land driven convection during summer, typically associated with large thunderstorms, and sea driven convection during autumn and winter, found in synoptic-scale weather systems which transport cold continental air masses over the relatively warm Mediterranean Sea water, leading to instability and convection, and generating smaller thunderstorm cells. For example, the thunderstorm producing 54 TLEs on 12 December 2009 including the first European GJ, was composed by several small cells with cloud top height of only 6 km (van der Velde et al., 2010a). Nevertheless, TLEs were observed to be produced by fewer but more prolific thunderstorms in autumn rather than in summer. The shift of TLE activity from the continental areas in summer to sea and coastal areas in autumn and winter is therefore abrupt both in the region of activity and in the leading processes driving the TLE production.

The observed evolution of the TLE distribution is remarkably consistent with lightning activity reported by the WWLLN network within the region of Eurosprite observations, similarly to the migration from land to coastal and maritime regions previously observed over the oceans (Füllekrug et al., 2002). The adoption of a observational sensitivity map based on actual regions covered by each camera and the related simulated TLE climatology allows to better interpret the main features of the observed climatologies, assigning them to either observational limitations or lightning activity. Considering the number of shortages that were not included in the calculation, the agreement between the observed and simulated climatologies is remarkable. On the one hand, dedicated studies can be planned to further inspect specific regions and try to resolve the differences in terms of observational capabilities. On the other hand, this comparison also throws light on possible differences in the behavior of TLE-producing thunderstorms in terms of production rates: can one expect the same TLE to lightning rate for all thunderstorms? Our results point to a very good consistency in the majority of cases but cannot exclude large differences. Discrepancies will therefore need to be further investigated inspecting the +CGs/-CGs ratio or further characteristics of the thunderstorms themselves, which vary in autumn/winter maritime thunderstorms as compared to summer continental ones, when this information will be available over continental scales. This includes also a larger fraction of high charge moment change and high peak current lightning, respectively needed for sprite and elve generation (e.g. Pasko et al., 2011). The climatological approach will aid in the comparison to relevant electrical and atmospheric parameters at large scale.

In agreement with previous studies of European TLE-producing thunderstorms (Neubert et al., 2001; Neubert et al., 2005, 2008; Soula et al., 2010; van der Velde et al., 2010b), the majority of TLE-producing thunderstorms in 2009-2013 were relatively small and reported to produce a small number of TLEs as compared to large thunderstorm observed e.g. in North or South America (Lyons, 1996; Taylor et al., 2008). The power law we found describing the number of thunderstorms producing a certain number of TLEs was novel and not reported before. This power law behavior is not unexpected, since it is often found in several other natural phenomena, such as when describing the occurrence and intensity of e.g., tornadoes, fires, earthquakes (see the review by Pinto et al., 2012). Furthermore, it is also found in describing the distribution of terrestrial gamma ray flashes (TGFs), the second type of exotic emissions produced by thunderstorm activity (Smith et al., 2005). Since the power law was found to be consistent over the 4 most prolific years, it suggests a possible new pathway for modeling the occurrence and distribution of TLEs and TLE-producing thunderstorms above Europe and other regions, so as to further fill the gaps in the observations and allow inclusion in global models (see e.g. the parametrization adopted by Arnone et al., 2014). Given a large sample of TLEs (e.g. from satellites intermittent passages over Europe), the scaling to obtain yearly rates should be performed clustering the observations over individual thunderstorms as described by the power law. It also allows a new approach for comparing the distribution of TLE-producing thunderstorms over different regions of the globe.

A selection mechanism due to better visibility in winter cannot be excluded to have contributed to observing more elves, halos, upward lightning and blue jets during autumn/winter, besides the expected higher rate of occurrence of elves over the sea. Comparison to Chen et al. (2008) and Newsome and Inan (2010) shows that a strong selection mechanism exists in ground optical observations in favor of sprites: the elve to sprite detection ratio in our climatology is in fact only 1:17 as compared to roughly 6:1 (30:1 accounting for detection efficiency corrections) found by the ISUAL satellite (Chen et al., 2008), and 6:1 found by ground using high time resolution photometer array (Newsome and Inan, 2010). However, the detection of elves almost exclusively over maritime thunderstorms is well in agreement with what found by previous studies (Chen et al., 2008). Besides shortages in the optical sensitivity to elves, the algorithms used for identifying elve images in the video frames are also less effective than for sprites. A similar detection bias occurs for halos, which we observed with a 1:27 halo to sprite ratio, whereas in the ISUAL satellite observations it was reported around 4:5. The consequences of different detection efficiency was discussed also by Williams et al. (2012). This further underlines the robustness of a joint TLE climatology, considering together TLE-producing thunderstorms, which are often observed to produce several types of TLEs, some of which have likely been missed.

As discussed, a key shortage of the adopted dataset is the inhomogeneity of the observational coverage. Cameras are often moved to different locations or pointing directions, or their views can be affected by the cloud coverage along their lines of sight. Besides, some cameras are used to track the evolution of thunderstorms (i.e. their pointing direction follows the peak activity), other cameras constantly cover the same region (i.e. they have a fixed pointing direction). The large number of cameras involved are likely overcoming some of this inhomogeneity and the adopted observational sensitivity map was shown to aid in correctly interpreting the results, further improving the comparison with the simulated climatology. The consistency of the observed TLE seasonal changes with the lightning activity shows that the climatological approach is robust. This novel climatology therefore represents an ideal reference for several TLE space missions (e.g. GLIMS, ASIM and TARANIS) operating over the next few years, and the joint use of ground and space-based observations will improve our simulation and the possibility of extending the climatology outside its current limitations.

6 Conclusions

We presented a first climatology of TLEs over Europe and the Mediterranean Sea based on a coordinated database of optical observations by the Eurosprite ground based network from 2009 to 2013. The main features of the TLE seasonal cycle were found to be robust, repeating over the years and consistent with lightning activity. The main TLE activity shifts from continental areas in summer to coastal and sea areas in late autumn and early winter. The largest number of TLEs per month is recorded in November, aided by the longer nighttime duration. In March and April TLE activity is almost completely halted, which considering the availability of continuously operated cameras and agreement with lightning activity cannot be due to a bias in active observational campaigns. Elves are observed almost exclusively over autumn-winter maritime thunderstorms, whereas sprites and halos follow the seasonal changes from land to sea.

Taking in consideration both observational coverage and lightning activity into a joint simulation, the consistency of the observed TLEs with lightning activity confirms nighttime lightning is a good proxy for TLEs at large scale and highlights regions were further studies are needed to optimize observational shortages or investigate possible peculiarities in the TLE production. Our analysis points to a 4/1000 (1/1000) TLE to (nighttime) lightning ratio, which applied to a global lightning rate of 44 flashes/s would lead to a TLE global rate of 2.6 TLE/min (largely a sprite global rate in our case), i.e. consistent but on the high hand of previous estimates in literature. Further consideration of detection efficiency for individual cameras and WWLLN lightning data will need to be adopted to further refine such estimate and the overall climatology. We also found that given a large sample of TLEs, a power law can well describe how to distribute the expected number of TLE per thunderstorm. These features should be taken into account when investigating the global impact of TLEs onto the atmosphere and parametrizing TLEs into global models. They can also be a valuable guidance for new ground-based observations and current or upcoming space missions.

Despite the consistency on these general features, we found some geographical discrepancies and different rates in some months (e.g. May and September) comparing TLEs to lightning. This confirms that disclosing the details of TLE activity requires further investigation in relation to the type of lightning (e.g. +CG/-CG ratio and intensity) and electrification mechanisms. The proposed climatological approach may lead to further advances also in this direction, by comparing large TLE samples to key atmospheric parameters. The very low rate of elve and halo observations is also evidence of the strong limitation of ground-based optical cameras for their observation, stimulating once more a needed synergetic approach with space missions such as ASIM. At the same time, ongoing Eurosprite activities will attempt to remove the main gaps in the observational coverage of Europe and the Mediterranean sea, including observations from regional all-sky camera networks which have developed over the last years.

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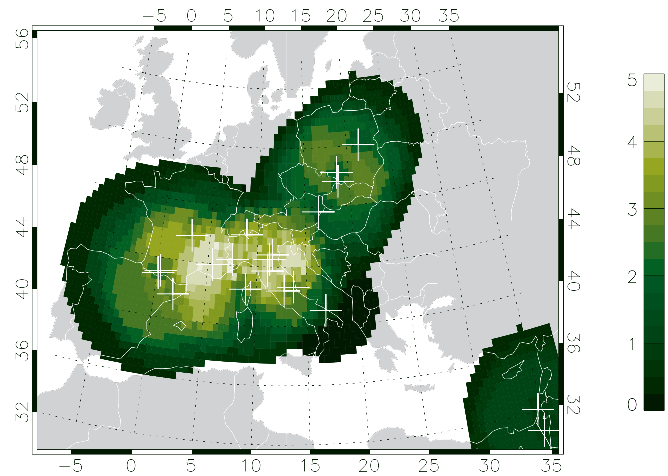

Figure 1. Location (white crosses) and estimated observational coverage (color scale) of the main optical camera systems involved in the Eurosprite network. The coverage is reported in terms of number of cameras observing a specific location weighted by the continuity or shortages of the contribution of each camera. See text for details.

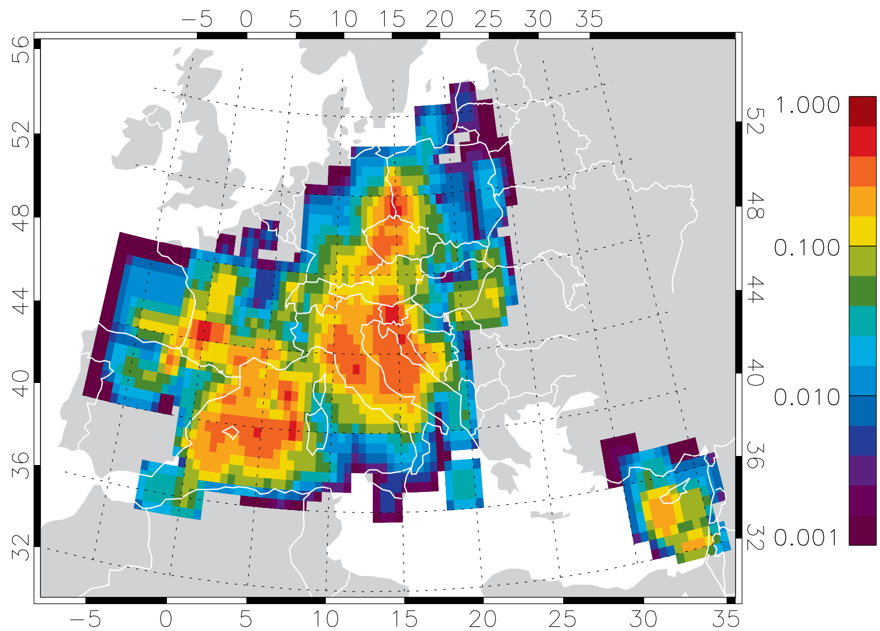

Figure 2. Climatology of observed TLEs (TLEs 10^{-3}km^{-2} yr^{-1}) for 2009 to 2013.

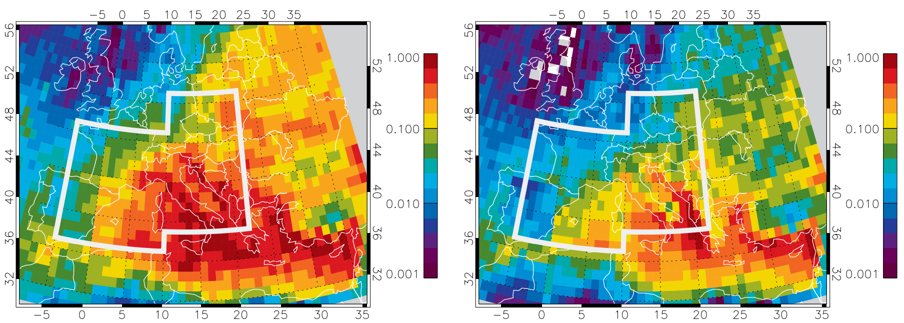

Figure 3. Climatology of lightning strokes detected by WWLLN (strokes $\mathrm{km}^{-2}\mathrm{yr}^{-1}$) for 2009 to 2013 considering the whole day (left) and nighttime only (right) counts. The white thick contours delimit the approximate area of TLE observations used in monthly mean calculations of WWLLN data.

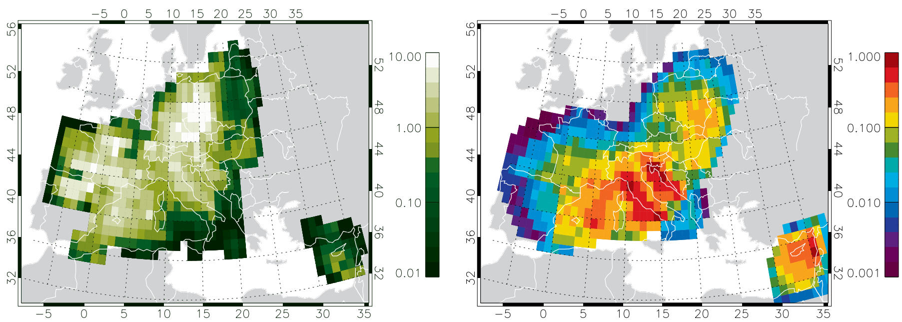

Figure 4. Left – Ratio of observed TLEs to 10^3 WWLLN nighttime strokes for 2009 to 2013. Right – expected TLEs based on WWLLN nighttime strokes (see Fig. 3), observational coverage (see Fig. 1) and an average 4/1000 TLE to nighttime stroke ratio (see left panel).

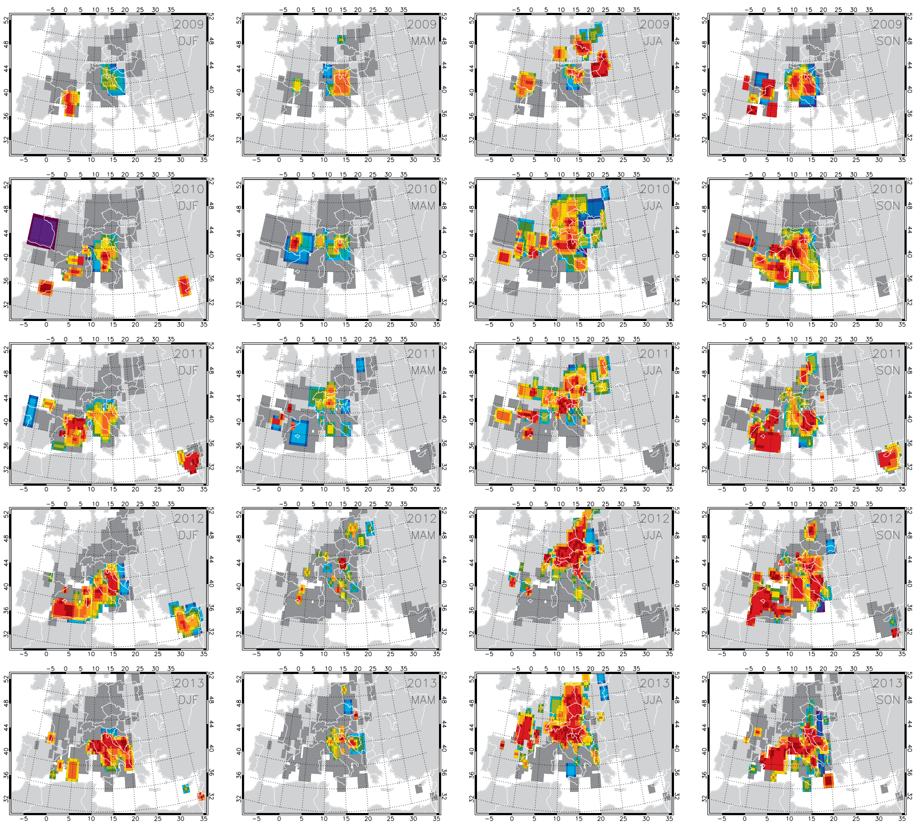

Figure 5. Climatology of observed TLEs (TLEs $10^{-3}\mathrm{km}^{-2}\ \mathrm{yr}^{-1}$) for individual years 2009 to 2013 (top to bottom) and season winter (DJF: December, January, February), spring (MAM), summer (JJA) and autumn (SON) (left to right). The area of data coverage of each individual year is shaded in dark grey. Color grading refers to color bar in Fig. 2.

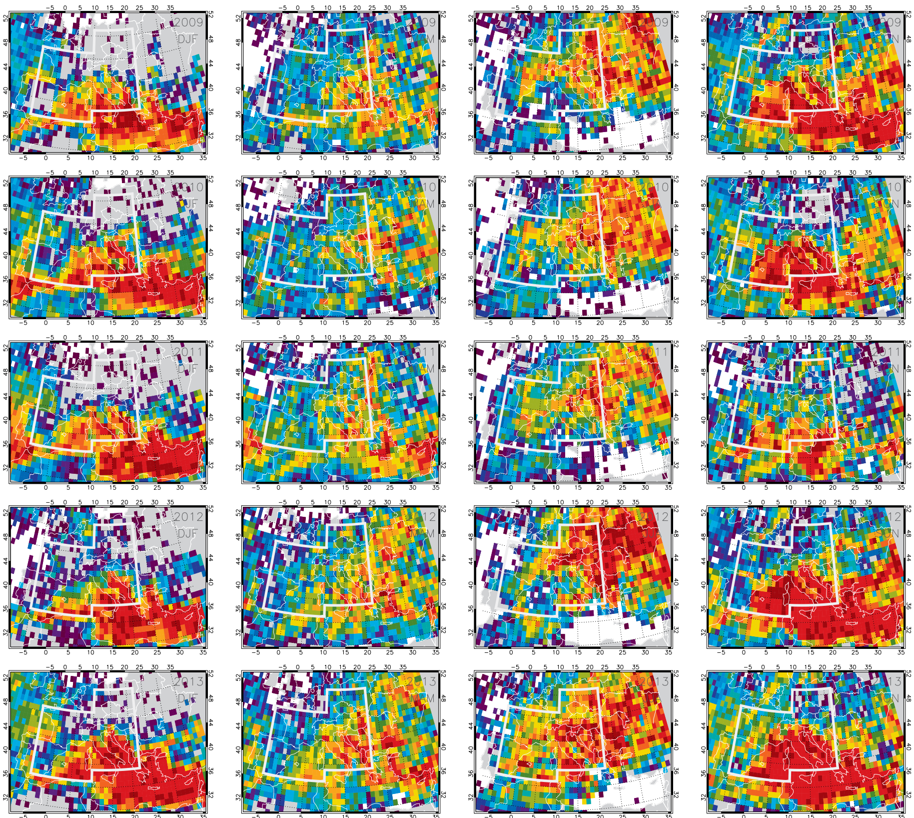

Figure 6. Climatology of nighttime lightning strokes detected by WWLLN (strokes $\mathrm{km}^{-2}\mathrm{yr}^{-1}$) for individual years 2009 to 2013 (top to bottom) and season winter (DJF: December, January, February), spring (MAM), summer (JJA) and autumn (SON) (left to right). White thick contours of the approximate TLE coverage (Fig. 3) are shown to ease comparison to TLE maps. Color grading refers to color bar in Fig. 3.

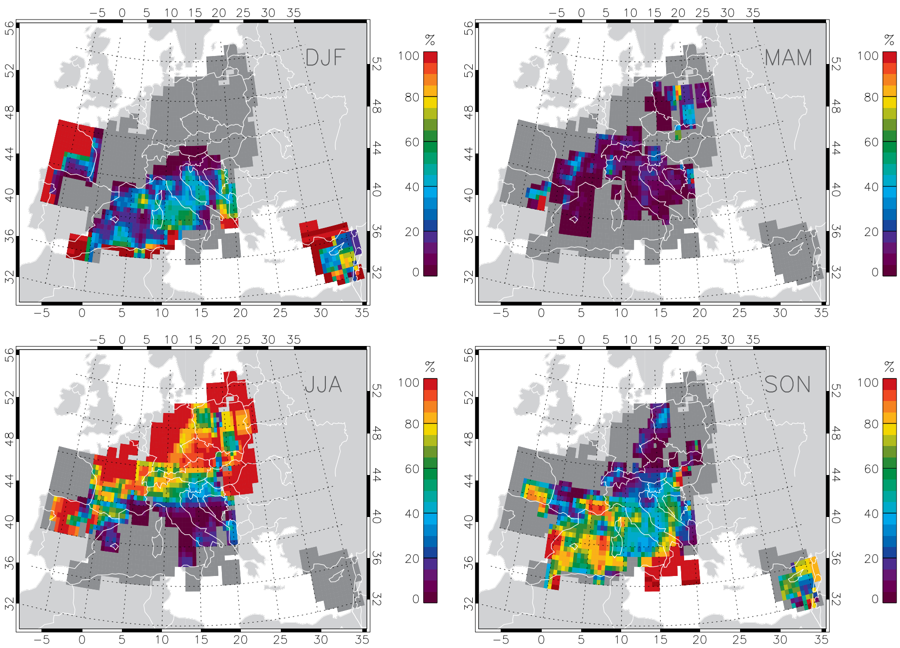

Figure 7. Average seasonal variation of TLEs (see labels). Data are reported as seasonal fractional component of the 2009-2013 average of Fig. 2. The area of data coverage of the complete data set is shaded in dark grey.

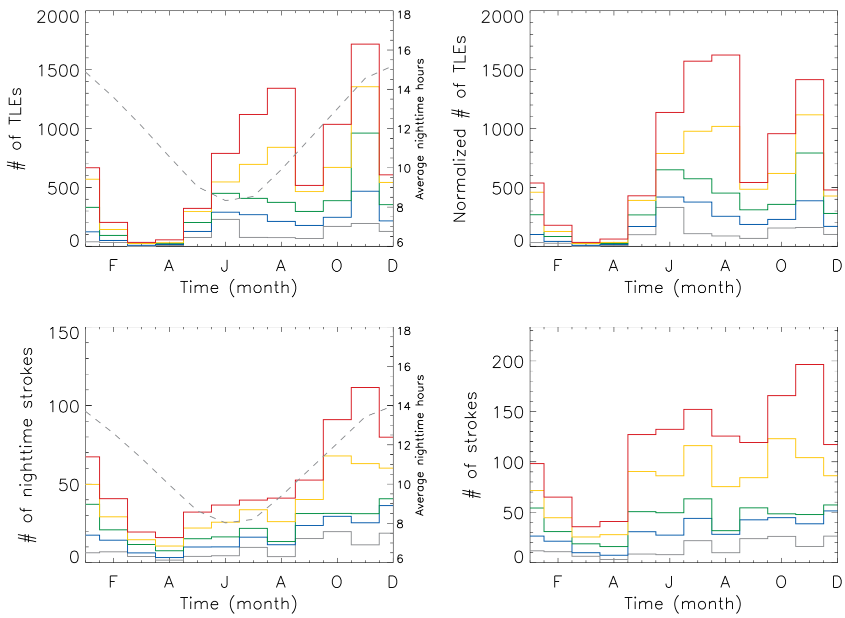

Figure 8. Cumulative number of observed TLEs (top) and WWLLN CG strokes (bottom) per month including data from the start of the sample (January 2009) to the end of 2009, 2010, 2011, 2012 and 2013 (respectively in grey, blue, green, yellow and red). Panels in the left column show TLEs and nighttime strokes; the average seasonal cycle of nighttime hours is shown in dashed grey. Panels in the right column show TLEs normalized to a costant 12-hour nighttime and WWLLN strokes during the whole day. WWLLN data are scaled by a factor 10^4 and averages calculated over the rectangular shapes shown in Fig. 3.

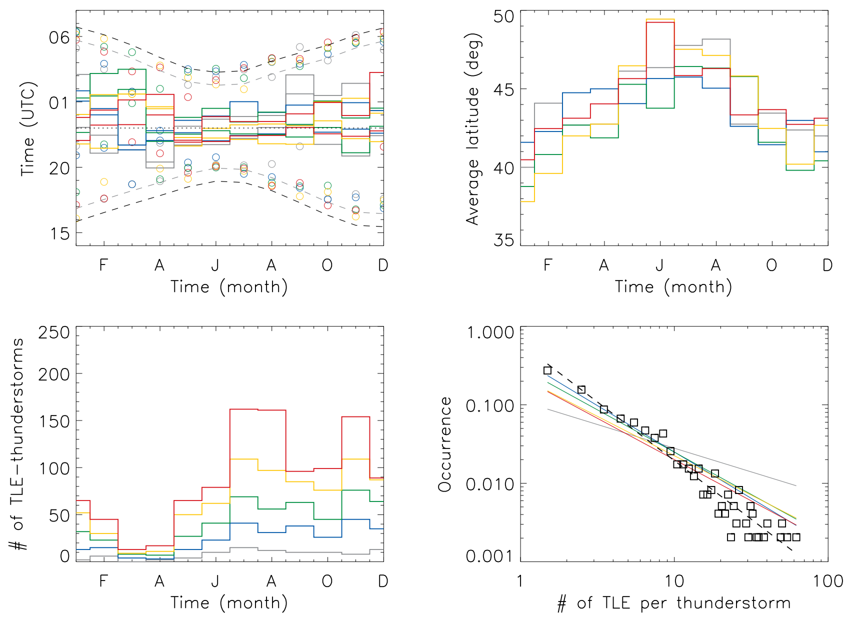

Figure 9. Top panels show the seasonal evolution of the average time (left) and latitude (right) for 2009, 2010, 2011, 2012 and 2013 (respectively in grey, blue, green, yellow and red). Time is shown as average start and average end of observations (step lines) and first and last observation (circles) of each month. Dashed lines show the seasonal evolution of the average sunrise and sunset (dark grey), and of an indicative 1 hour twilight (light grey). Bottom panels show the cumulative number of TLE-producing thunderstorms per month (left, color grading corresponds to Fig. 8) and the distribution of the number of TLEs per thunderstorms (right). A power law fit with correlation coefficient –0.96 is shown (dashed black line), together with power law fits for individual years 2009 to 2013 (colors as in top panels).

Table 1. Summary of the 30 most prolific TLE-thunderstorms observed in 2009 to 2013.

Date	Time	Latitude	Longitude	TLE	Sprite	Elve	Halo
29-OCT-2013	17:48 / 5:32	39.0 / 40.5	3.0 / 7.5	195	193	0	2
10-JUN-2009	21:00 / 2:00	45.0 / 47.0	19.0 / 23.0	147	146	0	1
28-NOV-2011	18:26 / 2:48	37.0 / 40.0	3.0 / 7.0	140	131	8	1
30-AUG-2012	21:23 / 4:05	37.0 / 40.0	0.0 / 2.5	129	123	0	6
26-JUL-2013	20:28 / 2:23	44.0 / 44.5	-1.0 / 1.5	111	111	0	7
12-OCT-2012	20:15 / 4:40	38.0 / 41.0	1.0 / 4.5	107	98	4	5
06-AUG-2013	19:37 / 0:49	48.0 / 50.0	12.5 / 14.5	101	84	0	16
30-NOV-2009	23:14 / 6:07	38.0 / 40.0	4.0 / 6.0	96	0	0	0
28-NOV-2012	16:39 / 4:02	40.0 / 44.0	15.0 / 17.0	79	79	0	0
29-JAN-2012	21:18 / 6: 8	36.5 / 39.0	0.0 / 5.0	78	18	59	4
08-OCT-2009	18:17 / 0:47	43.0 / 44.0	2.0 / 5.0	77	0	0	0
12-NOV-2011	22:19 / 23:01	33.0 / 35.0	31.0 / 33.0	75	75	0	0
27-MAY-2009	21:10 / 2:18	42.0 / 46.0	12.0 / 16.0	69	69	0	0
22-NOV-2013	1:31 / 5:54	41.0 / 42.5	4.0 / 8.0	62	10	50	2
20-AUG-2012	20:26 / 2:37	46.5 / 49.5	9.0 / 14.5	62	61	0	1
25-DEC-2013	21:34 / 6:21	43.5 / 47.0	-7.0 / -1.0	61	14	47	5
09-NOV-2010	19:59 / 5:30	43.5 / 44.5	-5.5 / -0.5	58	0	0	0
02-JUL-2012	20:15 / 1:32	49.5 / 52.0	12.0 / 16.5	54	51	0	4
12-DEC-2009	22:26 / 3:05	41.0 / 42.0	6.0 / 7.0	54	47	2	3
20-JUN-2013	21:26 / 1:14	50.5 / 54.0	11.0 / 16.5	53	53	0	0
02-AUG-2009	21:15 / 1:00	49.0 / 51.0	15.0 / 19.0	52	52	0	0
24-SEP-2012	17:47 / 22:24	45.0 / 47.5	12.5 / 18.0	50	50	0	0
02-JUL-2012	20:09 / 1:32	50.5 / 51.5	14.0 / 15.5	50	49	0	0
09-JAN-2012	0:26 / 5:30	41.5 / 43.5	14.0 / 16.0	50	50	0	0
24-NOV-2013	18:55 / 5:31	39.0 / 41.0	6.5 / 7.5	49	8	39	4
28-NOV-2010	19:31 / 3:45	43.5 / 45.0	-6.0 / -1.0	49	0	0	0
06-NOV-2011	18:01 / 23:25	42.0 / 44.0	13.0 / 16.0	46	2	0	0
25-JAN-2010	22:00 / 22:00	35.0 / 37.0	-3.0 / 0.0	44	40	4	0
20-JUN-2013	20:38 / 0:43	51.5 / 53.0	14.0 / 15.0	43	38	0	5
20-AUG-2012	19:18 / 3:04	47.0 / 49.0	9.5 / 13.5	42	42	0	0